THE DISTRIBUTION OF THE TRIPLET REFLECTOR IN THE NORTHWESTERN GULF OF MEXICO AS OBSERVED ON HIGH-RESOLUTION SUBBOTTOM PROFILES

A Thesis

by

LAURA LEE STANLEY

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Chair of Committee,	Niall Slowey
Co-Chair of Committee,	Mark Everett
Committee Member,	Alan Young
Head of Department,	Michael Pope

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ABSTRACT

A regionally persistent sequence of closely spaced, parallel reflectors known as the Triplet was studied using high-resolution profile data and sediment core data collected throughout the slope of the Gulf of Mexico. When reflectors are regionally persistent, they may be of value for two reasons: their distribution provides important clues about the nature of broad-scale environmental processes, and they can serve as reference horizons for both scientific and engineering applications. Sediments accumulating in the northwest Gulf of Mexico serve as an archive for glacial-interglacial changes in climatic and oceanographic conditions. Specifically, it is thought by other researchers that the Triplet marks a significant flux of terrigenous sediments into the Gulf of Mexico at the end of the last glaciation, which happened when glacial meltwater from the Laurentide Ice Sheet and associated Lake Agassiz flowed through the Mississippi River drainage. In this study, the occurrence and character of the Triplet was carefully documented using reflectors on high-resolution subbottom profiles collected during twenty-eight surveys of various locations across the continental slope. Analysis of this data was conducted using the IHS Kingdom seismic software platform, and sediment physical properties and radiocarbon ages from a previous study provided a means to ground truth the reflectors. Synthetic seismograms generated from sediment physical properties were quite similar to actual subbottom profiles, and synthetic seismograms corresponding to incrementally increasing sedimentation rates were compared to regional changes in actual reflector character. Results show the characteristics of the Triplet reflectors change with distance from the Mississippi River in ways that are consistent with it being the source sediment variations that produced the reflectors.

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1. INTRODUCTION

Sequences of continuous closely spaced, parallel reflectors are commonly observed on high-resolution seismic profiles of continental margins, including the seabed of the northwest Gulf of Mexico. Some reflectors occur in only limited areas, while others occur over large regions. When reflectors are regionally persistent, they may be of value for at least two reasons: their distribution provides important clues about the nature of broad-scale environmental processes, and they can serve as a reference horizon that is useful for both scientific and engineering applications. One reflector that appears to be broadly distributed is referred to as "the Triplet" *[Slowey et al., 2003; Young et al., 2003]*. A better understanding of where it does/does not occur along the continental slope and rise of the Northwestern Gulf of Mexico and the way that its acoustic character varies across this region will make a significant contribution to our understanding of global environmental processes and will be quite useful for practical marine engineering/geological purposes.

The Triplet is important because it is a valuable reference horizon for practical engineering and geological investigations. The Triplet corresponds to a short, known age interval, so its stratigraphic position relative to other geological features (other sediment layers, slumps, slides, debris flows, etc.) places a constraint on when they formed [e.g., [*Slowey et al.*, 2003; *Young et al.*, 2003]. When the Triplet is cut through by a fault or eroded by seafloor currents, the age of the Triplet can be used to estimate the timing and rates of these processes [*Angell et al.*, 2003; *Brand et al.*, 2003; *Slowey et al.*, 2003]. Finally, the Triplet can be a datum/context for understanding how sediment properties (density, shear strength, etc.) reflect the environmental history of that area [*Young and co-workers*, unpublished].

The Triplet may also mark an important environmental event. Sediments accumulating in the northern Gulf of Mexico serve as an archive for glacial-interglacial changes in climatic and oceanographic conditions. One important way relates to the growth/decay of the Laurentide Ice Sheet (LIS). The LIS was the largest North American glacier and its history is linked to global environmental conditions during the past 20,000 years when sea level was ~120m lower than it is today [*Fairbanks*, 1989; *Flint*, 1957; *Imbrie and Imbrie*, 1986; *Ruddiman and Wright*, 1987]. As the LIS began to retreat with a warming climate the glacier began to melt in a series of pulses, causing sea level to rise rapidly. Oxygen isotopic records derived from foraminifera in sediment cores collected in the Gulf of Mexico point to a major influx of isotopically light glacial meltwater routed from the LIS via the Mississippi River drainage system ~15-12 kyr BP [*Kennett and Shackleton*, 1975; *Leventer et al.*, 1982]. The history of eustatic sea level reconstructed from corals drilled offshore of Barbados indicates two major meltwater pulses between 14-10 kyr BP [Fairbanks, 1989]. LIS meltwater accumulated in glacial Lake Agassiz, the world's largest volume of freshwater at that time [*Teller and Clayton*, 1983]; when Lake Agassiz reached mass capacity, basin runoff was initiated through outlet erosion at the southern margin, which created overflow channels and led to a lower lake water level [*Teller et al.*, 2002]. Deglacial meltwater flow was greatest during the Bolling warm interval (~12.7-12.2 kyBP) , then it was disrupted by an anomalous period of cooling known as the Younger Dryas (~11-10 kyBP) [*Broecker et al.*, 1989; *Flower and Kennett*, 1990]. It is thought that the amount of glacial meltwater that entered the Gulf of Mexico was greatly diminished after ~9500 yr BP [*Broecker et al.*, 1989]. During the deglaciation, meltwater from North American glaciers that did not flow down the Mississippi River, entered the oceans through one of three other major drainage basins:

the St. Lawrence Valley, the Mackenzie River Valley, and the Hudson Strait [*Broecker et al.*, 1989; *Teller et al.*, 2002].

The ~14-10 kyr BP pulses of meltwater correspond to major rises in global sea level/volume (~18 x 10^6 km^3) inferred from Barbados corals [*Fairbanks*, 1989]. Variations in the flow of LIS meltwater and locations where it enters the oceans are thought to have affected ocean circulation and the climate of Europe, North America, and other parts of the world [e.g., [*Broecker et al.*, 1989; *Clark and Mix*, 2000; *Rooth*, 1982; *Teller et al.*, 2002]. While the time period of ~15-9 kyBP has been well studied, knowledge of the important beginning part of the transition from the last glacial maximum to the present and its relation to the history of the LIS is limited. *Aharon* [2003] showed at least one significant meltwater spike in the Gulf of Mexico 16 kyBP. The LIS was at maximum extent during the Last Glacial Maximum (before ~18 kyr BP) when sea level was ~120 m lower than the present [*Fairbanks*, 1989], and climate has been generally considered to relatively stable [*Clark and Mix*, 2000; *Dyke et al.*, 2002]. However, a high-resolution foraminifera oxygen isotope record from the Mad Dog and Atlantis Developments, *Slowey and Guilderson* [unpublished] shows a series of meltwater spikes in the Gulf of Mexico during the beginning part of the deglaciation, with the oldest occurring 19-20 kyBP. Interestingly, changes in the assemblage of foraminifera in the Bonaparte Gulf of Australia [*Yokoyama and Esat*, 2004] and the sediment type in the Irish Sea basin [*Clark et al.*, 2004] are consistent with an abrupt rise of global sea level at about 19 kyBP. *Clark et al*. [2004] suggest that the seal-level rise originated somewhere in the North Hemisphere and it somehow contributed to warming of the Southern Hemisphere and tropics while maintaining cold Northern Hemisphere climate. A better understanding of earliest deglacial events will help show mechanisms involved in the shift from glacial to interglacial climate and propagation of global climate signals.

Slowey and Young [personal communication] believe that they have evidence that leads to an understanding of what occurred during the earliest portion of the deglaciation. Their unpublished data clearly indicates that at that time meltwater from the LIS did enter the Gulf of Mexico. At the Mad Dog and Atlantis developments discrete, relatively dense silt layers bounded by clays result in prominent reflectors on high-resolution seismic profiles that are referred to as "the Triplet" [*Slowey et al.*, 2003; *Young et al.*, 2003]. *Slowey, Young, and co-workers* [unpublished] have recognized these same sedimentological and seismic features at widely separated areas along the continental slope of the northwestern Gulf of Mexico. It is well known that wind-blown silt called "loess" is found throughout the basins of the Mississippi and Missouri Rivers in central North America [e.g., [*Ruhe*, 1983]. The rate of loess deposition was high when the LIS extended into these basins [*Johnson and Follmer,* 1989; *McKay,* 1979; *Ruhe,* 1983; *Willman and Frye*, 1970], and a chronologic framework for this loess deposition during the past 40 kyr late has been developed [*Forman et al.*, 1992]. *Slowey and Young* [personal communication] hypothesize that catastrophic release of LIS meltwater from glacial Lake Agassiz brought vast quantities of loess down the Mississippi to the Gulf of Mexico and made the Triplet's sedimentological and seismic features. If true, North American climate actually began to warm during the earliest deglacial and it initiated the changes in both global sea level and climate. It is worth noting that sediment accumulation rates measured at widely separated locations on the slope are consistent with the Mississippi River being the dominant sediment source during the last glaciation [*Slowey and Young,* unpublished, and this thesis].

Given the Triplet's importance as a marker horizon used by engineers and geologists investigating seafloor sites in the northwest Gulf of Mexico and that the Triplet potentially marks a significant event in the recent glacial-to-interglacial climate transition, a better understanding of the broad-scale seismic expression of the Triplet is necessary. The research here focuses on several aspects of the Triplet as observed on high-resolution seismic profiles collected in the northwest Gulf of Mexico during seafloor geohazard surveys.

2. HYPOTHESES

Several working hypotheses were evaluated during this research:

- *The likelihood of the Triplet occurring in a local sequence of seismic reflectors is greater the closer a locality is to the Mississippi River.*

Why? The Mississippi River is the presumed source of the sediments that cause the acoustic impedance contrasts within the seabed, which are expressed seismically as the Triplet.

- *In general, the Triplet will be found deeper below the seafloor at localities that are close to the Mississippi River.*

Why? Triplet sediments were deposited during the Last Glacial Maximum, when rivers delivered much sediment to the continental slope of the northwest Gulf of Mexico. The Mississippi River is by far the largest of these rivers. Sediment from it would have been deposited at high rates for thousands of years after the Triplet was formed, burying the Triplet. This general pattern may shift in areas where seafloor currents transport sediments laterally.

- *The seismic character of the Triplet will depend on distance from the Mississippi River.*

Why? The spacing between the individual layers of sediment that make up the Triplet will vary as the sedimentation rate and distance from the Mississippi River change.

3. GEOLOGICAL/OCEANOGRAPHIC SETTING

This study is focusing on the Texas-Louisiana Continental Slope in the Gulf of Mexico and limited portions of the continental rise. Water depths in this region range from about 200 to 3,000 m. The slope is the most geologically complex area in the Gulf of Mexico (Figure 1) and is dominated by salt tectonics, faults, oil and gas seeps, acoustic wipeout zones, and other features affecting near-surface sediments [*Bouma et al.*, 1990]. The salt bodies and sediment loading have structurally deformed overlying deposits and created bathymetric highs, resulting in basins, bounding ridges, and hummocky slope geometry. The Sigsbee Escarpment, marked by a dramatic increase in gradient, is located on the southern/seaward edge of the continental slope. Down-slope sediment transport in the Gulf of Mexico is often associated with the deposition of riverine sediments on the seaward edge of the continental shelf and the upper continental slope, which triggers processes including turbidity currents, mass transport deposits, and debris flows [*Prior et al.*, 1989]. Today, the Mississippi River drainage system is the primary sediment source for this region depositing an average of 210×10^6 metric tons of sediment per year and is transported a great distance through sediment entrainment and near-bottom turbidity currents [*Milliman and Meade*, 1983; *Milliman and Syvitski*, 1992]. During periods in the Pleistocene when large continental glaciers existed on North America, much greater amounts terrigenous sediments were transported to the Gulf by meltwater runoff; these fine-grained hemipelagic sediments are important because they can be dated at high resolution and used to reconstruct continental events [*Brown and Kennett*, 1998].

Sedimentation rates are heavily influenced by sea level fluctuations. During ice ages sea level is represented as a lowstand and during interglacials it is represented by a high-stand

[*Lambeck and Chappell*, 2001]. From the last glacial maximum to the late Holocene a decrease in sedimentation rate was observed as sea level rose in the Gulf of Mexico beginning around 20 kyr BP [*Greenman and LeBlanc*, 1956; *Slowey et al.*, 2003].

4. PALEOCEONOGRAPHIC TOOLS

4.1 Acoustic Record

In this study we use the subbottom acoustic record as a paleoceonagraphic tool to investigate the origin and geologic significance of the Triplet reflector sequence. High-resolution subbottom profile data contains higher frequencies than conventional low-frequency data and enables detailed mapping of the seabed and near seafloor features. If such profile data is be used to investigate the relationships between geologic horizons within the seabed, and the lithologic significance of the seismic reflectors must be understood [*Mayer*, 1980; *Slowey et al.*, 1989] .

How are hemipelagic sediments deposited along the continental slope of the northwest Gulf of Mexico during the last glaciation and deglaciation expressed on seismic profiles? Typically, the echo character of sediments deposited along the slopes of continental margins and in the deep sea by hemipelagic processes display a sequence of closely-spaced, laterally continuous parallel reflectors [sees *Damuth*, 1980]. Reflectors on high-resolution chirp subbottom profiles from the continental slope of the northwest Gulf of Mexico do have this expected echo character (e.g., [*Bouma et al.*, 1990; *Tripsanas et al.*, 2007]). The Triplet sequence is a package of high-intensity reflectors associated with strong impedance contrasts (see Figure 5) Slowey and Young determined that the top of the Triplet corresponds to sediments deposited slightly more than 18,500 yrs. BP and the base of the Triplet corresponds to sediments deposited about 20,000 yrs. BP, when the LIS was at its maximum extent during the Last Glacial Maximum [*Slowey et al.*, 2003; *Young et al.*, 2003]. While high-intensity reflectors tend to correspond to particularly large acoustic impedance contrasts [e.g., [*Damuth*, 1980; *Slowey et al.*, 1989], variations in character of high-resolution seismic reflectors can result from differences in the separation of closely-spaced sediment layers because these differences affect how reflections from individual sediment layers interact with each other [*Mayer*, 1980; *Slowey et al.*, 1989]. The character of reflectors present over a long distance across the continental slope of the Gulf of Mexico appears to vary, perhaps as the deposition rate and composition of the sediments varies and depending on the quality and setting of the geophysical data.

4.2 Synthetic Seismograms

A synthetic seismogram is a simulated seismic response derived from velocity and density measurements that are used to correlate seismic facies and reflections with core data [*Mayer*, 1980; *Payton*, 1977]. From bulk density (ρ) and sound velocity (v) measurements, the acoustic impedance (AI) can be calculated for each interval of sediment in the seabed, where $AI=\rho*v$. The reflection coefficient (RC), which is the amplitude of the seismic energy reflected from the interface between two intervals of sediment relative to the amplitude of incident energy, is defined as $(AI_2-AI_1) / (AI_2+AI_1)$. Thus, acoustic impedance is an important acoustic property because the way it varies determines the nature of reflectors observed on subbottom seismic profiles.

In this study one sediment core, which is described in more detail below, was studied from the northwest slope of the Gulf of Mexico. It is important to examine the two factors that determine variations in AI in this particular core: sound velocity and saturated bulk density (Figure 2). The velocity versus impedance regression for this core yielded a correlation coefficient of $r=0.69$ while the bulk density correlation was $r=0.99$ (Figure 3). Mayer [1980] points out that a stronger relationship between density and impedance often exists in marine sediments because there is a wider relative range of bulk density values than velocity values.

5. DATA SETS

5.1 Sediment Core Data (CSS-1)

Sediment core CSS-1 was recovered landward of the Sigsbee escarpment within the Atlantis offshore development. The length of the core was ~18.5 meters. Measurements of sediment bulk density and velocity shown in Figure 2 were obtained every two centimeters down the core and ages of sediments at various depths in the core were determined based upon radiocarbon dating and variations in the oxygen isotopic compositions of foraminifera shells, as well as nannofossil occurrences [Slowey et al., 2003; Young et al., 2003]. Based these measurements, down-core variations of acoustic impedance were calculated and reflection coefficients were derived. Sediment chronology, physical property, and lithology data has also been related to the Triplet reflectors at other sites [*Slowey, Young, and co-workers*, unpublished].

Comparison of sediment property data and the reflectors on subbottom profiles collected adjacent to the site of core CSS-1 indicated the Triplet reflectors corresponded to an increases of both density and velocity associated with sediment layers containing high silt contents. Thus, the core data provided a valuable means to ground truth subbottom reflectors displayed in the vast amounts of high-resolution seismic data examined during this investigation. The way that the acoustic impedance structure changes from one location to another also influences how the acoustic character of reflectors changes from one location to another (discussed below).

5.2 Subbottom Profile Data

Commercial deep-water autonomous underwater vehicle (AUV) surveys are an integral part of modern geohazard site investigations conducted for the planning and development of deep-water oil prospects. In the Gulf of Mexico, much of this type of data has been collected by

C&C Technologies for various clients using an AUV that possesses a chirp subbottom profiler. Other data was collected by Fugro. Over the last decade Geoscience Earth & Marine Services (GEMS) of Houston, Texas has worked on highly integrated geologic and geotechnical engineering projects for deep-water developments in the northwest Gulf of Mexico that utilize AUV datasets. I worked closely with GEMS to identify a list of existing surveys with high-resolution 2D subbottom profile data appropriate for this study. This effort gained access to processed chirp subbottom profile data from twenty-eight surveys (Figure 4) distributed across various parts of the continental slope (middle, upper, and lower) and the continental rise.

The outgoing pulses are "chirped" or modulated in the frequency band of 2 to 8 kHz. In most cases, the data was acquired at an approximate depth of 40 meters above the seafloor using an Edgetech system mounted on a Kongsberg Hugin 3000 Autonomous Underwater Vehicle [*George et al.*, 2002].The acquisition systems have a built in processing component that is created by the manufacturer so detailed information about the "chirp" source wave form and way the data was processed are not available. When acquiring/processing chirp subbottom profile data, resolution was enhanced by match filtering, a processes in which the wave form of the source pulse was cross correlated with the raw reflection data [*Caress et al.*].

Each dataset that was used in this study included a corresponding geo-hazard report from the original survey assessment that contained useful components including acquisition parameters, location maps, and bathymetry and seafloor information. It is important to note that not every dataset was acquired using the same acquisition system and parameters, so there are differences (data quality, resolution, etc.) between each data set. Recognizing these variations, I assembled the available survey data sets and loaded them into The Kingdom Suite seismic interpretation platform to create two projects for this study. These projects correspond to the Universal Transverse Mercator Zones 15N and 16N. The data is referenced to the Geodetic Datum NAD27 with the Clarke 1866 Ellipsoid.

Data loading was a crucial first step in the process of preparing the digital SEGY formatted seismic data for visualization and interpretation. This step was accomplished using Seismic Explore, a tool within the Kingdom interpretation platform. The time data bounds were selected along with the coordinate reference system and the start time byte location, sample interval, and number of input sample/trace values had to be specified for each survey.

6. METHODS OF STUDY

6.1 Sediment Core to Seismic Correlation and Identification

The Triplet was studied on regional scale in the northwest Gulf of Mexico through detailed analysis and correlation of sediment core data, high-frequency subbottom profile data, and synthetic seismograms. In cross section, the Triplet feature appears as a package of typically two to three thin, dark parallel reflectors, and in some cases there are up to five reflectors that can be resolved depending on the resolution of the data. To positively identify the Triplet in subbottom profiles it is necessary to start at areas seismic reflectors have been ground-truthed by careful comparison with sediment core data, then to extrapolate away from these sites (Figure 5 and 6). One data limitation to note is that each subbottom profile survey was acquired at different times this means that there are notable differences in acquisition parameters, data quality (Figure 7). There is also a tremendous amount of data available so it was not possible to simply map out all of the reflectors in all instances. Instead a high density sampling of points along each survey was examined and recorded to document characteristics of the Triplet at each spot.

A 10-cm diameter piston core was used in a previous study to collect marine sediments from the Atlantis field [*Slowey et al.*, 2003]. Figure 8 shows chronostratigraphic age relationships of the Triplet and other high-resolution seismic reflectors derived from core CSS-1 and AUV seismic data at the Atlantis Development [*Slowey et al.*, 2003]. Sediment chronology, physical property, and lithology data has also been related to the Triplet reflectors at other sites [*Slowey, Young, and co-workers*, unpublished]. This data provides a valuable means to ground truth and correlate subsurface reflectors displayed in the vast amounts of high-resolution seismic data being examined for this project.

6.2 Spatial Variation and Distribution

Two important objectives of this study were to document the presence/absence of the Triplet reflector sequence across the continental slope of the northwest Gulf of Mexico and to illustrate how the characteristic features of the Triplet reflectors vary both north-to-south and east-to-west across the continental slope. This was done by compiling representative cross-section images of subbottom reflector data at various sites in a north-to-south and east-to-west progression across the slope (Figures 9-12). After this data was compiled, the images were flattened to the seafloor and scaled for comparison.

The Triplet reflector sequence is affected locally by geologic events (slides, slumps, debris flows, escarpment edge, etc.) so it may look different from one survey to the next. Flattening to the seafloor is a helpful technique that attempts to reverse the effects of geologic processes by removing all of the geologic structure present in the subbottom profile data. Scaling the data using a constant time was necessary because each data set was acquired with different parameters, so this gives a consistent way to view the data as if it were collected with the same system.

There are evident changes in the character of the Triplet reflectors with distance from the Mississippi River and Mississippi Canyon, which have implications for the potential source locations of the sediments corresponding to the Triplet as well as the processes that transported/deposited/eroded the sediments corresponding to the Triplet (discussed below). Next, I created scatter plots of measured values of Triplet reflector characteristics (number, thickness, depth below seafloor, and intensity) at various locations to explore interrelationships among these parameters. These plots are helpful in making inferences about the regional-scale depositional processes and sediment accumulation patterns that exited when the Triplet sediments were deposited.

6.3 Synthetic Seismograms

The primary objective of creating synthetic seismograms was to better understand the extent to which variations of AI with depth in the seabed affect character of the Triplet reflectors. First, data from core CSS-1 was scaled to simulate different rates of sediment accumulation and synthetic seismograms were generated. For this data set the first trace was 50% of the original core data sedimentation rate. Then each consecutive synthetic was generated for an incrementally increasing sedimentation rate (10% increments). The last trace represents a sedimentation rate that is double the original core data.

Next I generated a synthetic seismogram using a 1 kHz Ricker wavelet for comparison. The correlation between the synthetic trace and the subbottom profile trace is shown. By comparing the synthetic seismograms to actual seismic data collected at various sites, the influence of sedimentation rate on the seismic character of the Triplet might result could be assessed. The SeisLab 3.02 Matlab toolbox [*Rietsch*, 2015] was used to generate synthetic seismograms by convolving reflectivity coefficient series with a known wavelet. For this study I used a 2 kHz Ricker wavelet, which is a zero-phase wavelet with a central peak frequency and two side lobes. It is important to note that subbottom profile data is commonly presented as a positive-only envelope function because the cross correlate signal will mix positive and negative peaks and these may be difficult to interpret [Caress and Chayes, 2004] wavelet is not the same as the actual chirp pulse shape so the synthetic seismograms will not be exact matches with the real data. Nevertheless, the seismograms should still provide a good way to investigate potential influences of sedimentation rate changes on the seismic character of the Triplet. For this reason the synthetic seismograms generated for this study display positive only values that were generated by taking the absolute value of the reflection coefficients.

7. RESULTS

7.1 Reflector Sequence Spatial Distribution and Character

The 2D subbottom profile images in Figures 9 and 10 show the spatial distribution of the Triplet regionally across the slope of the Gulf of Mexico. The Triplet was first identified on subbottom profiles by comparing co-located core bulk density and acoustic impedance measurements with the reflectors, and then the reflectors were mapped away from the known location. I was able to identify the Triplet in all twenty-eight AUV data sets. The EW and NS extent are mapped constrained by the availability of subbottom profile data at those locations. These same images were flattened to the seafloor for comparison (Figures 11 and 12). It was important to look at the actual trace data (Figures 13 and 14) that comprises each subbottom profile line in order to gain a better sense for a regional correlation of the Triplet and to verify the presence at each location along the slope.

After determining where the Triplet was present at each data site, I took a high density sampling of points (Triplet thickness, location, and distance below the seafloor) and documented them in a spreadsheet. For each location I noted the number of reflectors, spacing of the reflectors in depth/travel time, and depth below the seafloor. The depth was estimated by using an average water velocity of 1500 m/s and using the two-way traveltime equation. The 3d plots were created to provide a quantitative basis for analyzing how to Triplet sediments vary on a regional scale in the Gulf of Mexico. Variances in the Triplet's overall thickness of the reflector sequence at different locations along the slope of the Northwestern Gulf of Mexico are shown in Figure 15. The data show the Triplet being thick near the mouth of the Mississippi River Delta and progressively becoming thinner towards the south-west. The plot indicates higher sedimentation rates near the mouth of the Mississippi River. This pattern is consistent with the source of the Triplet sediments being the Mississippi River drainage basin.

The relationship between the depth of the Triplet below the seafloor and distance below the seafloor is shown in Figure 16. The overall pattern shows that the depth of the Triplet is greatest depth near the Mississippi river and gradually becomes less towards the south-west. This pattern indicates higher sedimentation rates near the Mississippi and lower sedimentation rates towards the southern and western portion of the slope.

Figure 17 shows the number of parallel reflectors that comprise the triplet at various locations along the slope. Values range from two to four reflectors with the most common pattern being three, which is where the name was derived. Towards the northwest the Triplet is comprised of four reflectors and the number decreases to the south-west. These values provide important information regarding the origin of the Triplet and the nature and timing of each layer that comprises it.

As an aid to evaluating first-order trends in the spatial variation of the Triplet's seismic character, I fit surfaces to the data already shown in Figures15-17. Figure 18 shows the Triplet thickness versus latitude and longitude. I used a second order polynomial fit to represent the overall trend of the data. For Figures 19 and 20 I used a first order polynomial to model the data. The results substantiate the original hypotheses for this research.

7.2 Synthetics and Modeling

One-dimensional synthetic seismograms were constructed from velocity and density measurements taken from core CSS-1. The results shown in Figure 21 include the acoustic impedance, reflection coefficients, synthetic seismogram, and corresponding subbottom profile trace. The results are shown in Figure22. The differences seemed to be negligible between the two synthetic traces.

As a modeling exercise using synthetic seismograms, a series of synthetic seismograms were generated from core CSS-1 (Figure 23). The downcore physical properties were kept the same, while the sedimentation rates were increased. Mayer [1980] illustrates that by using this method we can determine if seismic reflectors correlate one-to-one with lithologic features in the seabed, or if reflectors are the product of the interference of multiple reflections off closely spaced features the seabed. Since the Triplet is the product of hemipelagic sediments that were deposited through meltwater influx, the character varies in response to sedimentation rates. Regionally, there is a remarkable consistency in the sedimentation patterns. The seismic reflectors remain constant even though the data changes from each location. This is consistent with the method of deposition where a large volume of sediment would have been deposited as a drape as the sediments settled out across the slope of the Gulf of Mexico.

8. CONCLUSION

The slope of the Gulf of Mexico is draped by a sequence of parallel reflectors comprised of hemipelagic sediments known as the Triplet. This research integrates high-resolution subbottom profiles collected regionally throughout the slope and sediment core data which were utilized to create synthetic seismograms to better understand the relationship between acoustic character and geologic physical properties. Several methods were used in a detailed analysis of the spatial distribution and presence along the slope. Using the high-resolution subbottom profile data this study examined the spatial variability of the Triplet (number of reflectors, spacing, and depth below the seafloor). In addition, synthetic seismograms were generated to better understand the relationship between acoustic character and geologic physical properties.

The data show that the Triplet sequence is thick near the mouth of the Mississippi River and progressively thins away to the southwest. Along with the change in overall thickness the number of reflectors in the package is found to be better preserved to the north. As you move south, the reflector package has fewer reflectors that comprise the sequence. Sedimentation rates were studied by the position of the Triplet relative to the seafloor. Near the Mississippi River delta the triplet is about 30 meters deeper than it is at the furthest data point studied, which indicates that the northern area is highly influenced by a riverine input. The Triplet sediments were deposited during the Last Glacial Maximum, when rivers delivered a large volume of sediment to the continental slope of the Gulf of Mexico. Since the Mississippi River is the presumed sediment source for these sediments that cause strong acoustic impedance contrasts, the Triplet is more likely to occur in a local sequence of seismic reflectors closer to the Mississippi River. The seismic character of the Triplet will depend on the distance from the

Mississippi River. The Triplet was found deeper below the seafloor at localities that are close to the Mississippi River. By documenting the rapid influx of sediment into the Gulf of Mexico we now further understand the importance of broad scale climate history related to the Laurentide Ice Sheet and its contribution to sea level rise over the last 20,000 years.

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APPENDIX

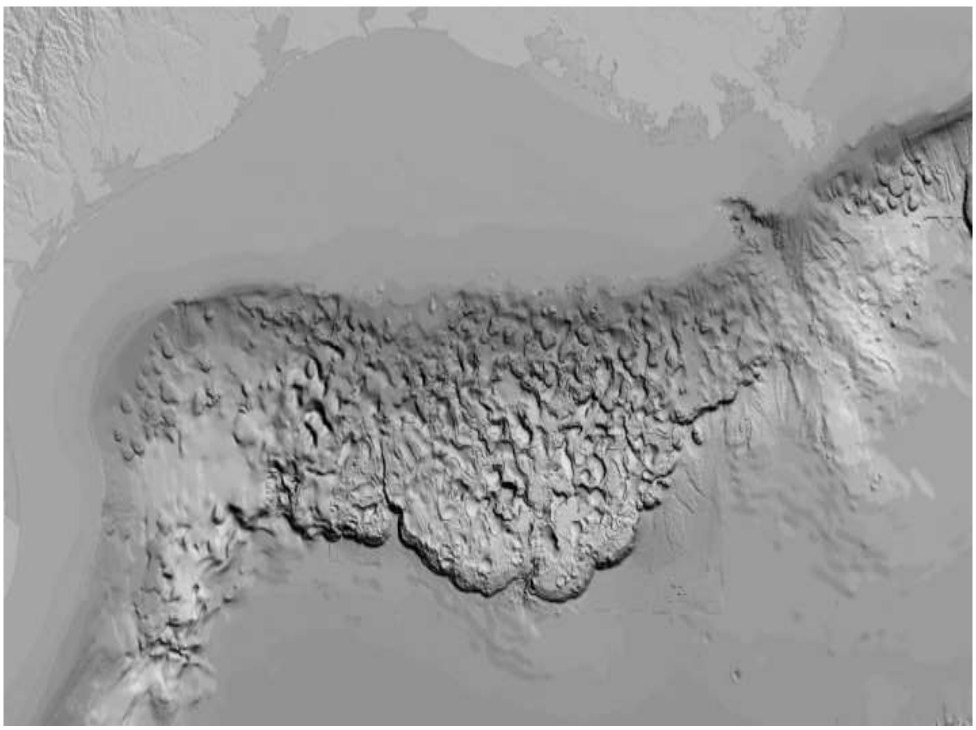


Figure 1. NOAA bathymetric map of the slope of the Northwestern Gulf of Mexico. This figure shows the geologic complexity of the slope which has been heavily affected by salt tectonics and other geologic events.

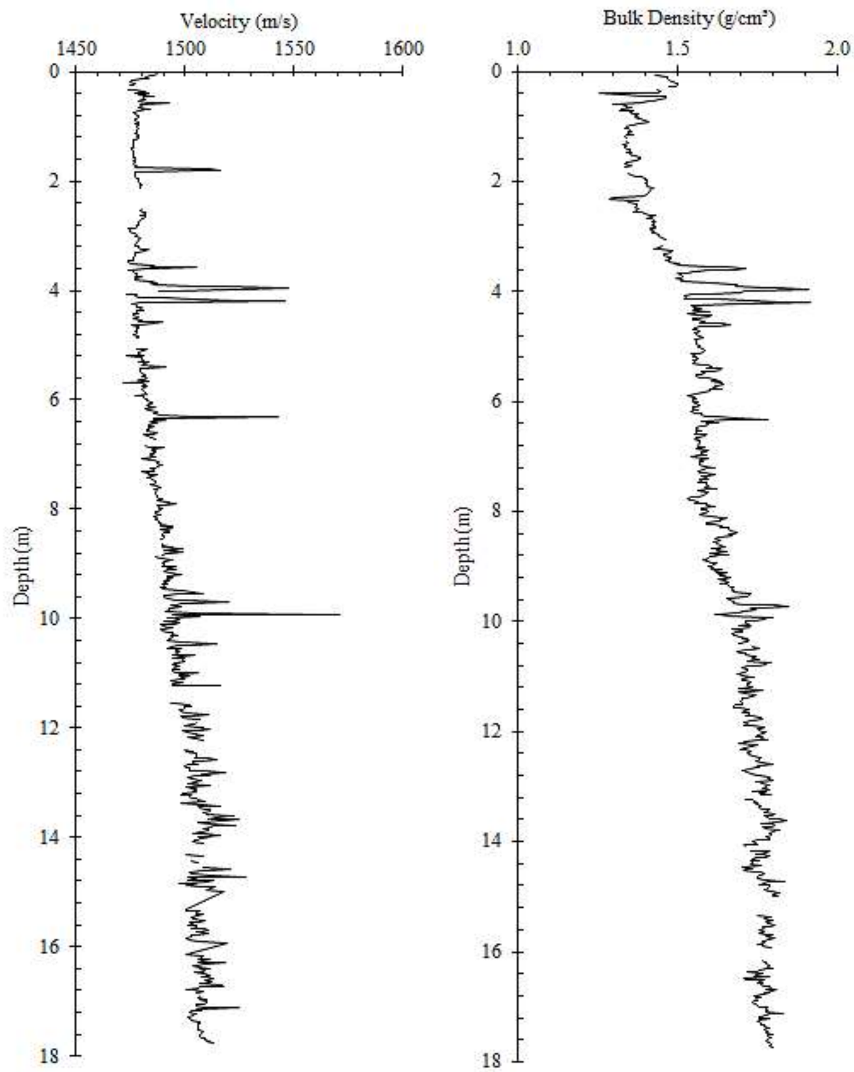


Figure 2. Core CSS-1 density and velocity profiles versus depth.

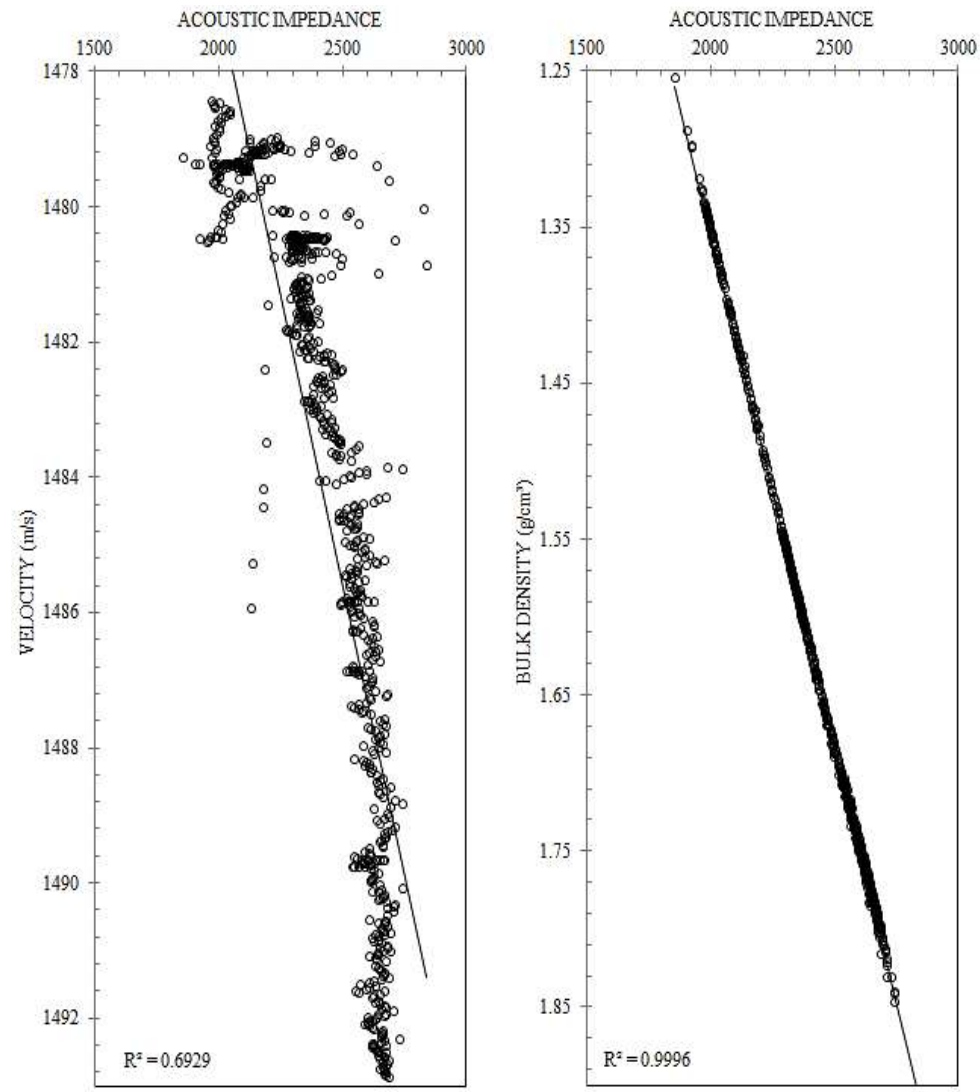


Figure 3. Linear regression (Core CSS-1) acoustic impedance versus velocity and bulk density. (r=0.6929 for acoustic impedance versus velocity; r=0.9996 for acoustic impedance versus bulk density) adapted from [Mayer, 1980].

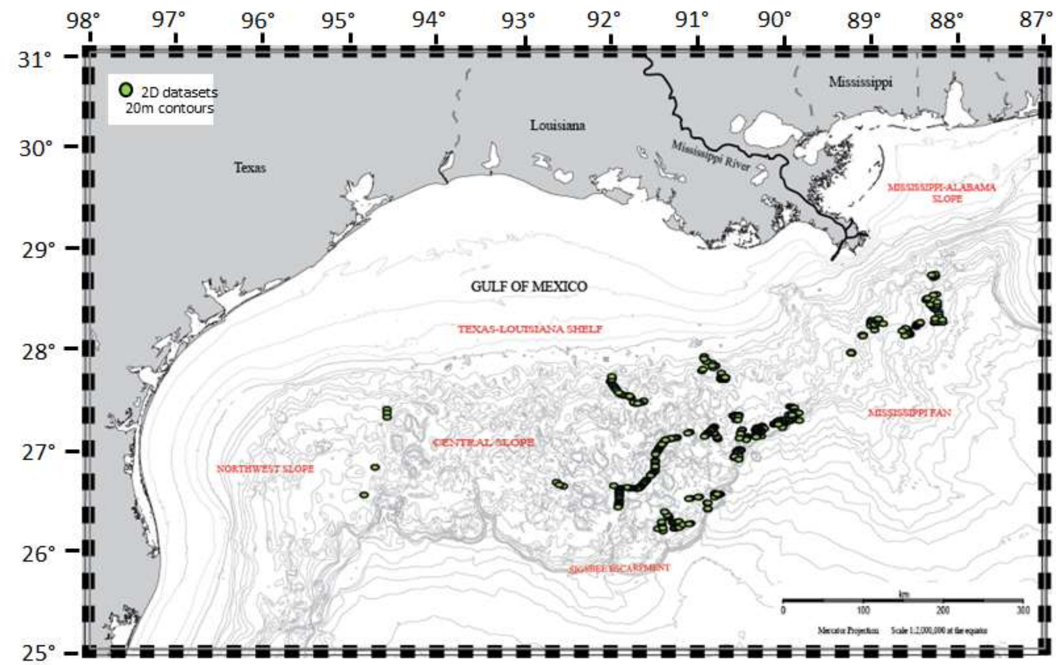


Figure 4. Location map of 2D high-resolution subbottom profile datasets available for this study Adapted from [*Holcombe et al.*, 2002].

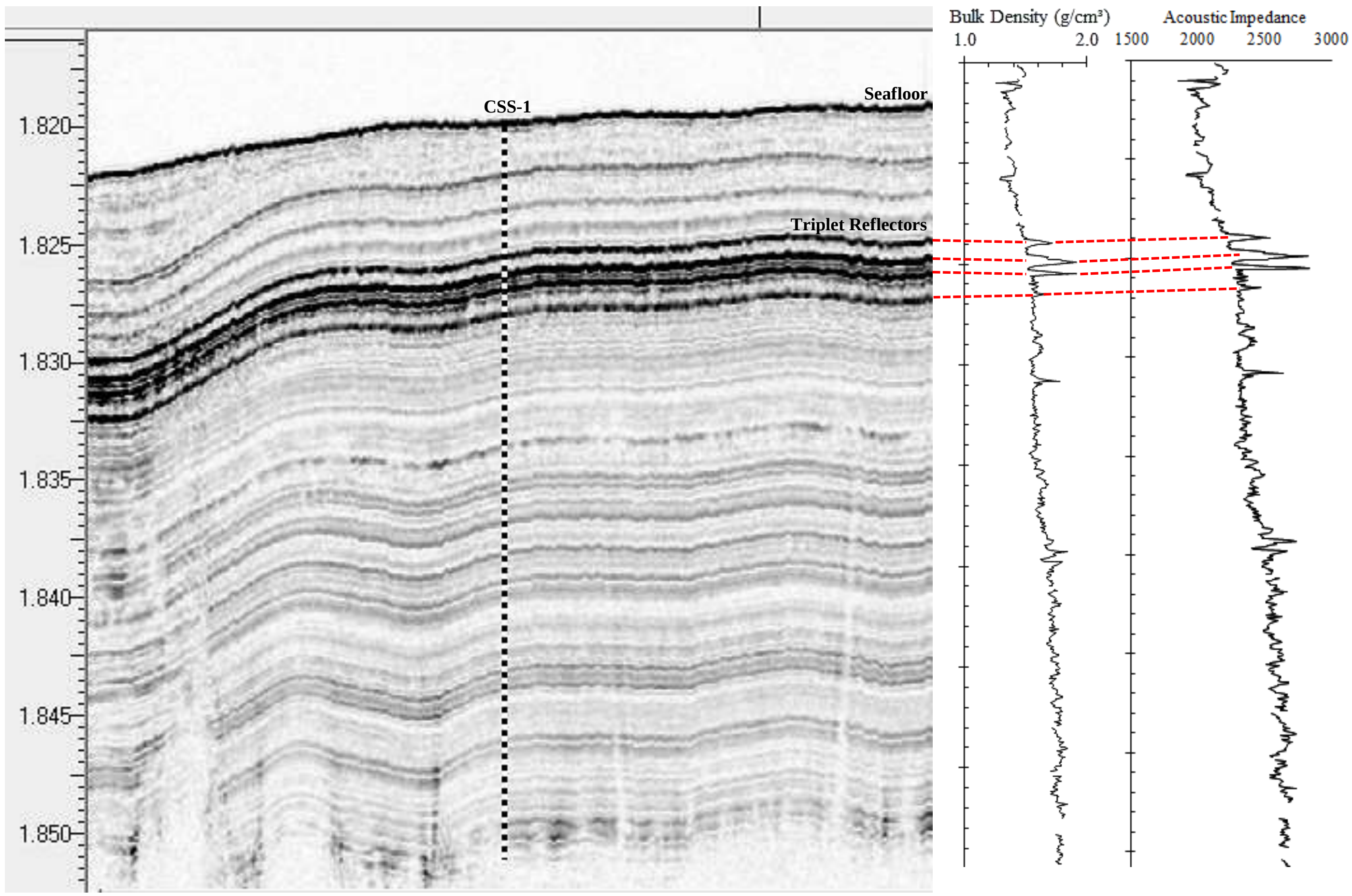


Figure 5. High-frequency subbottom data overlain by the projected well path of core CSS-1 showing the correlation of the Triplet. Correlations can be made to the Bulk Density and Acoustic Impedance profiles derived from core CSS-1 to verify the Triplet reflector sequence on the subbottom profile data.

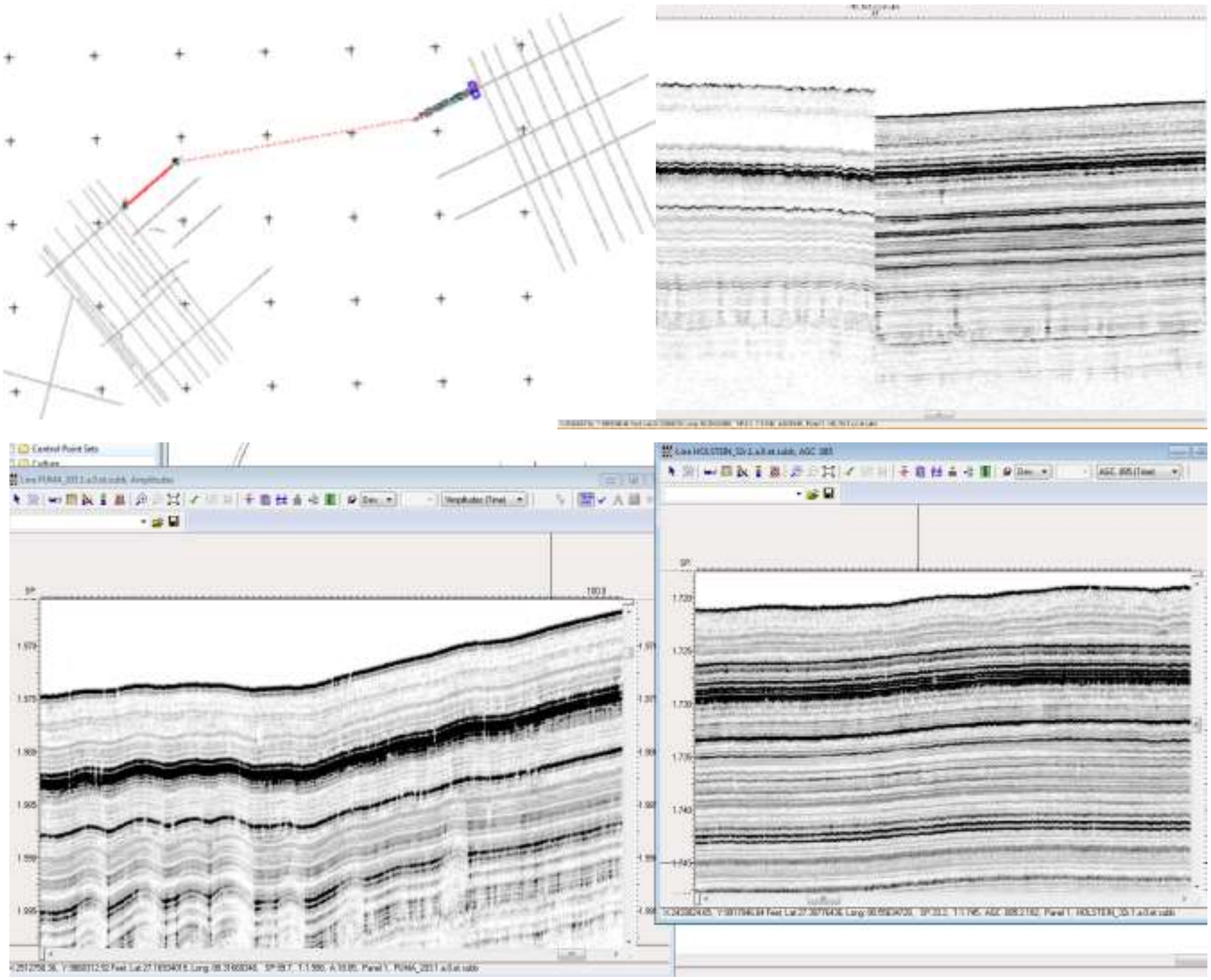


Figure 6. Subbottom profile seismic to seismic correlation.

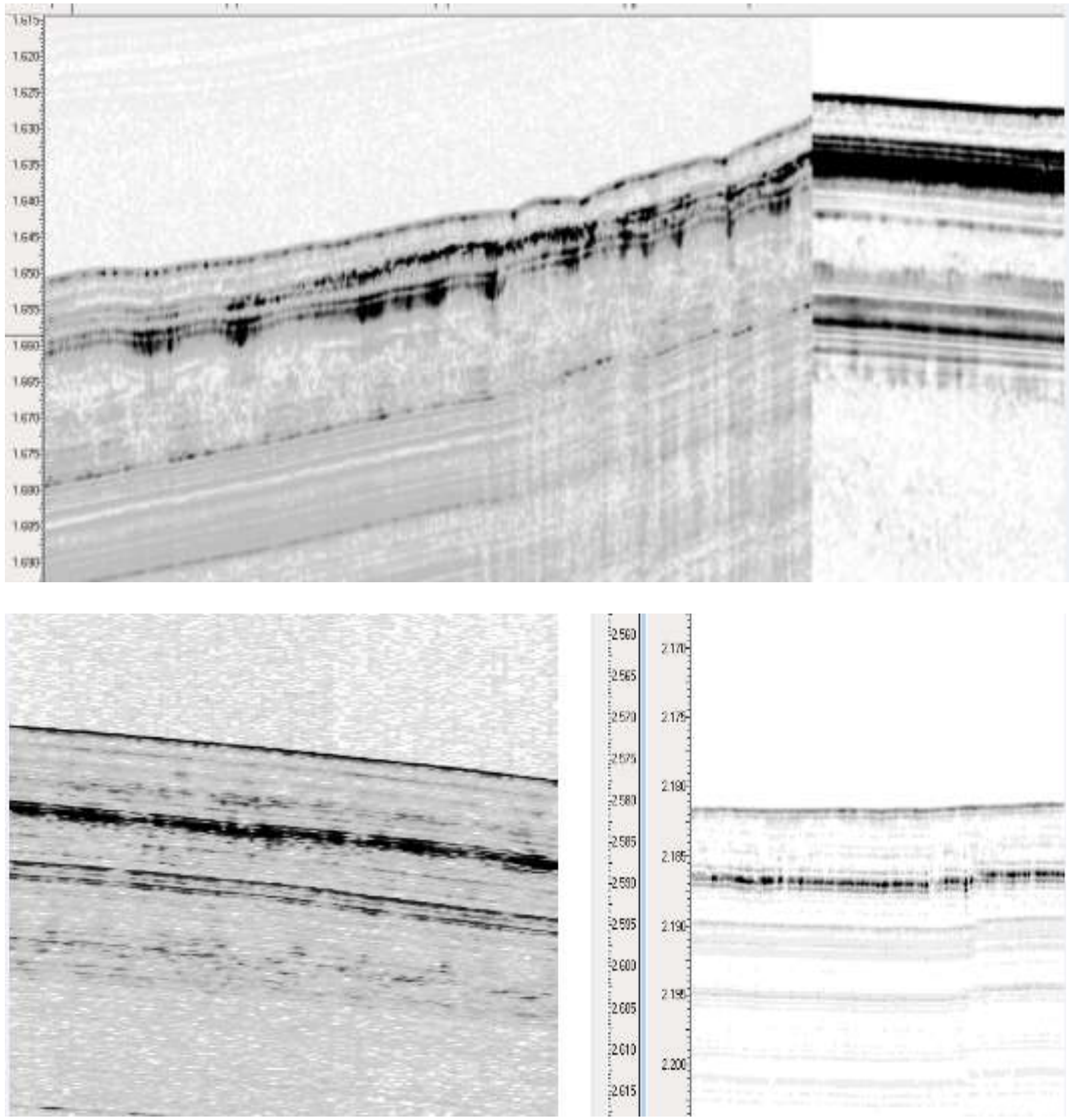


Figure 7. Data Limitation (Data Quality).

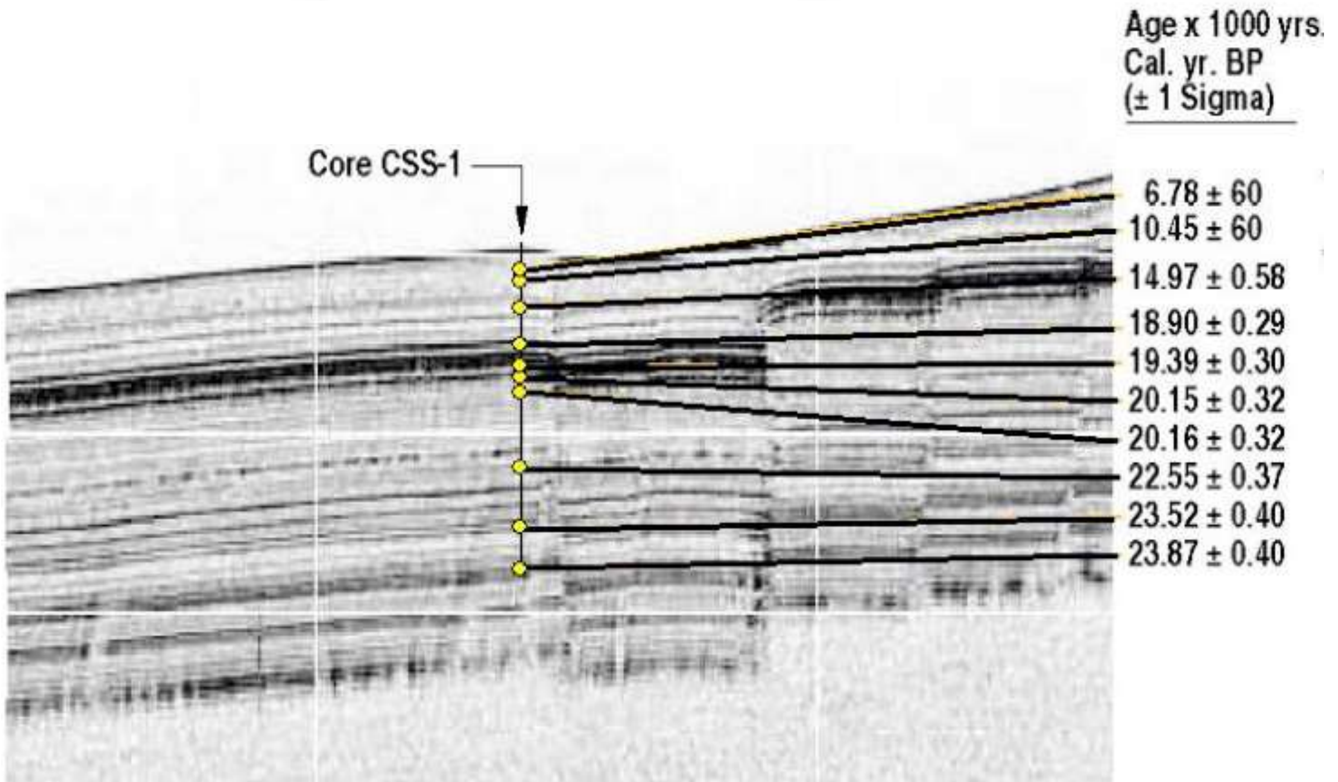


Figure 8. Radiocarbon ages for the Triplet and surrounding reflectors. High-resolution subbottom profile line showing the distinct series of reflectors age dated using the radiocarbon method adapted from [*Slowey et al.*, 2003].

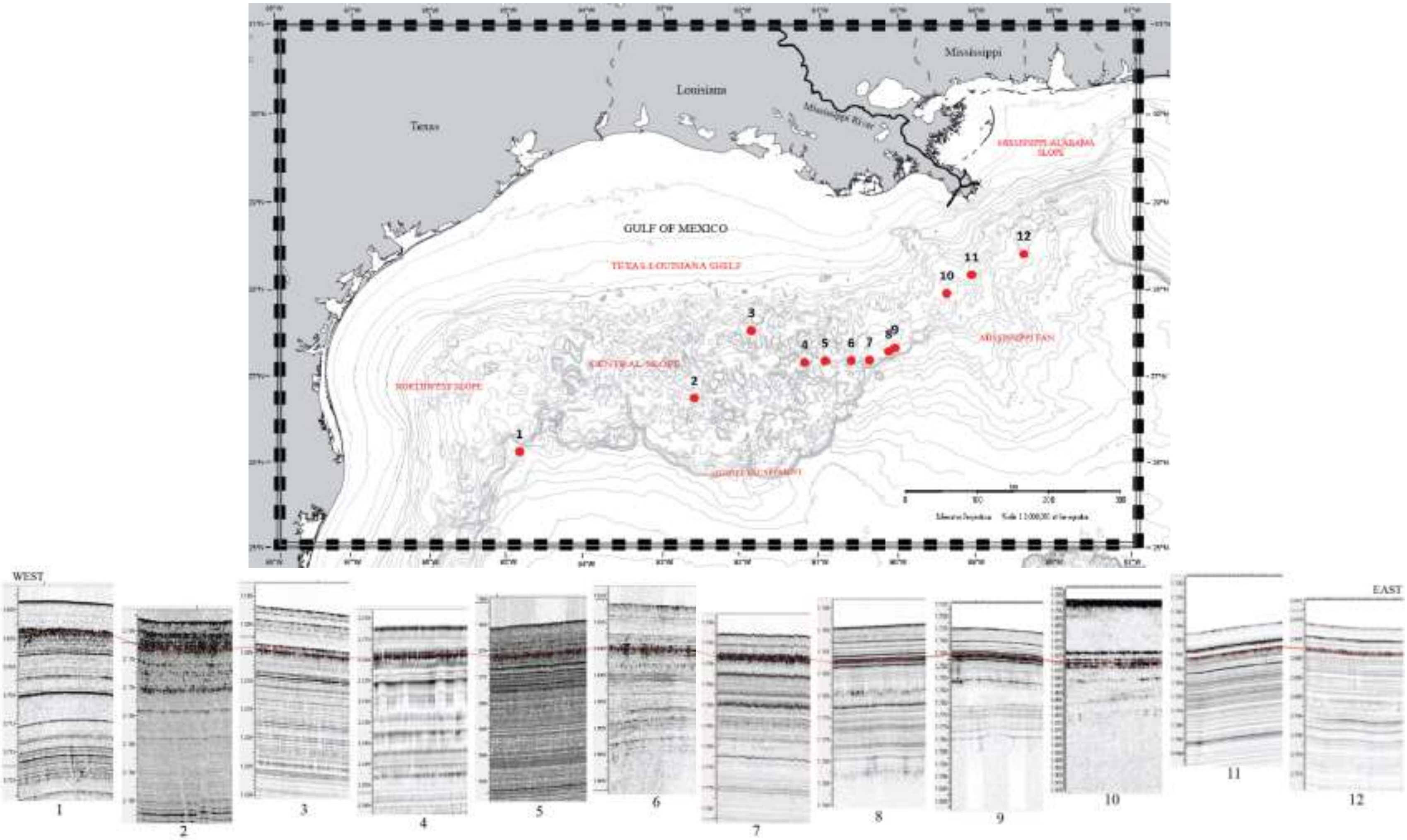


Figure 9. West to East progression of the Triplet in cross-section. The time scales have not been modified.

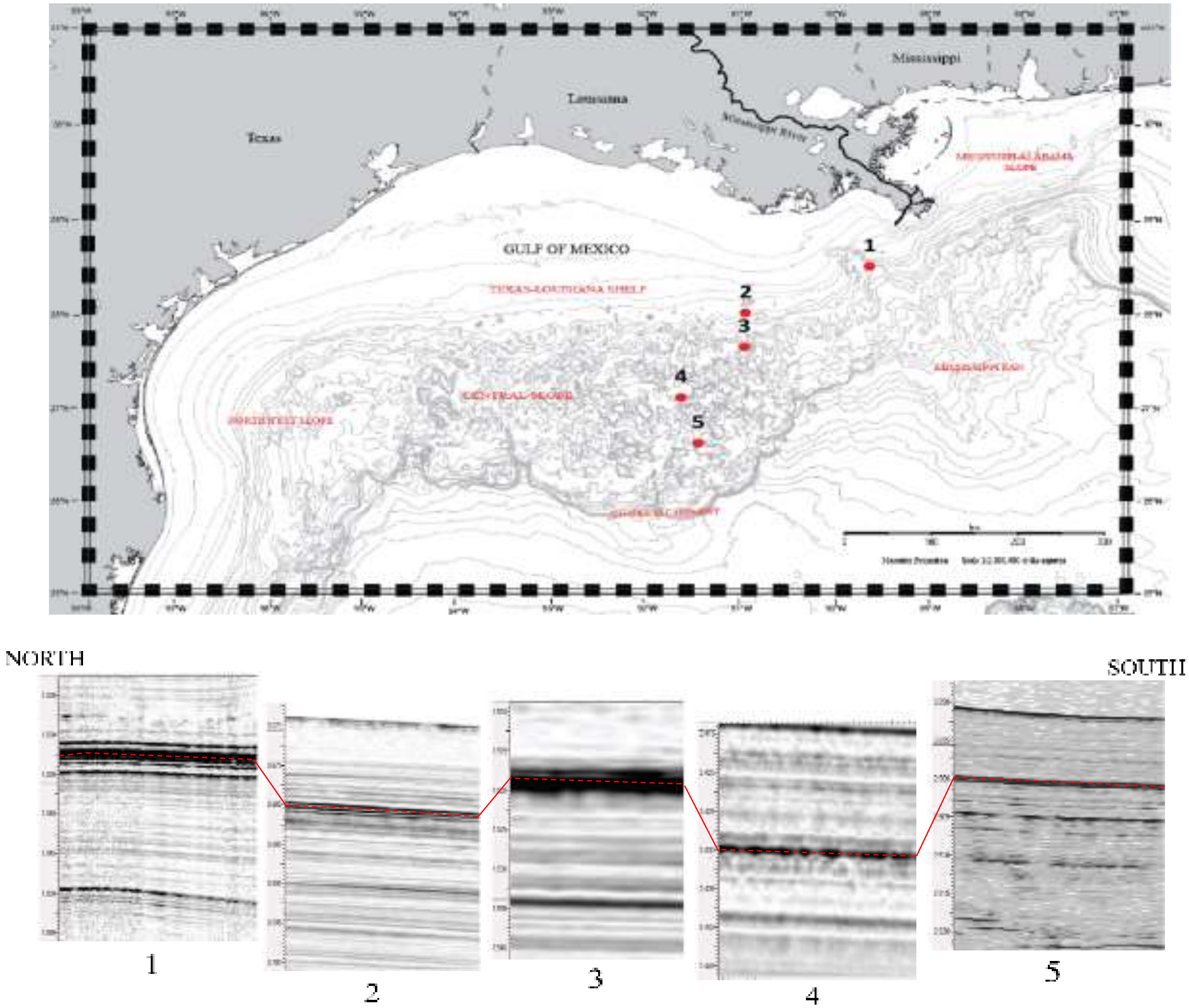


Figure 10. North to South progression of the Triplet in cross-section. The time scales have not been modified.

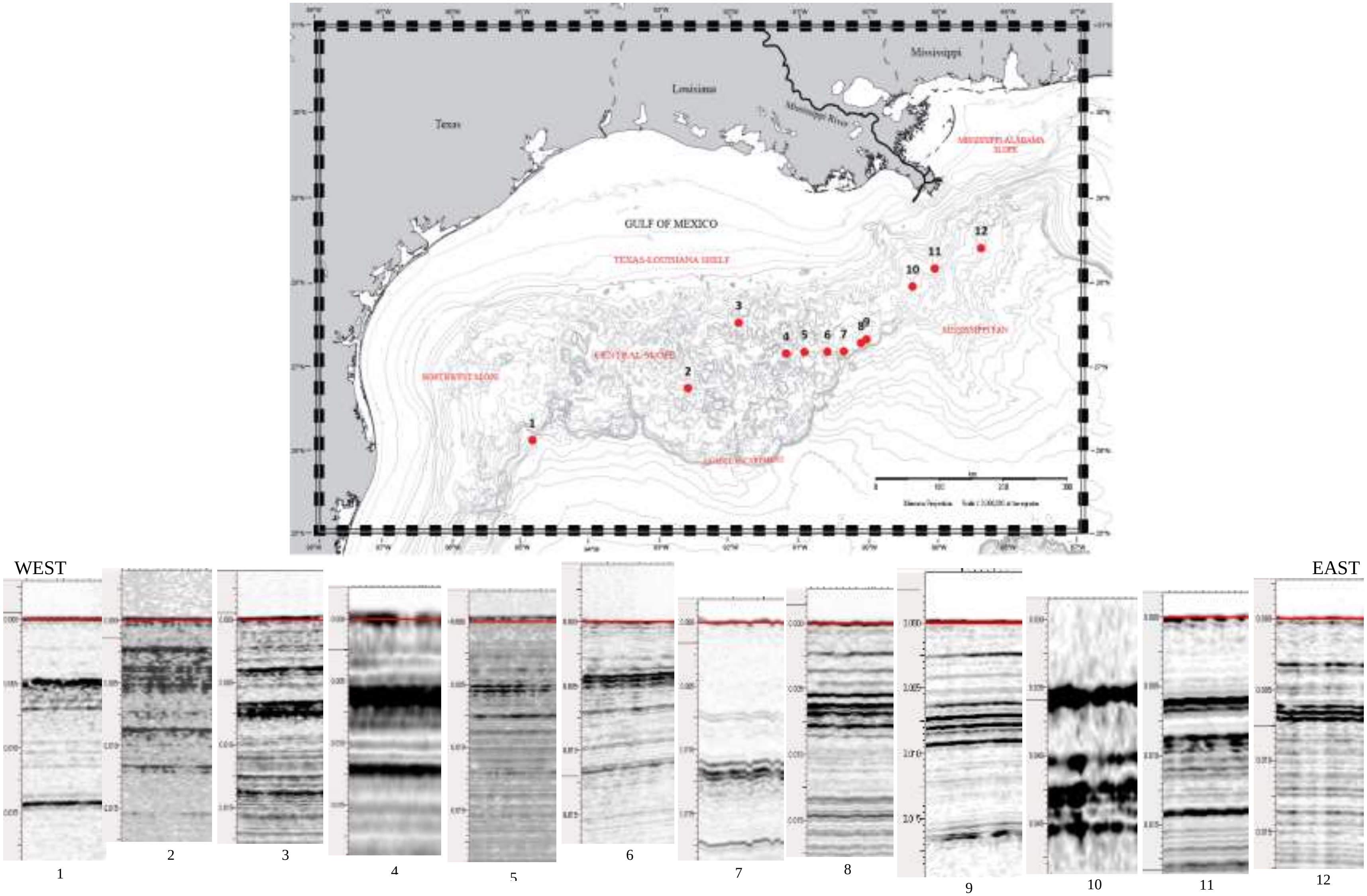


Figure 11. West to East progression of the Triplet in cross-section flattened to seafloor.

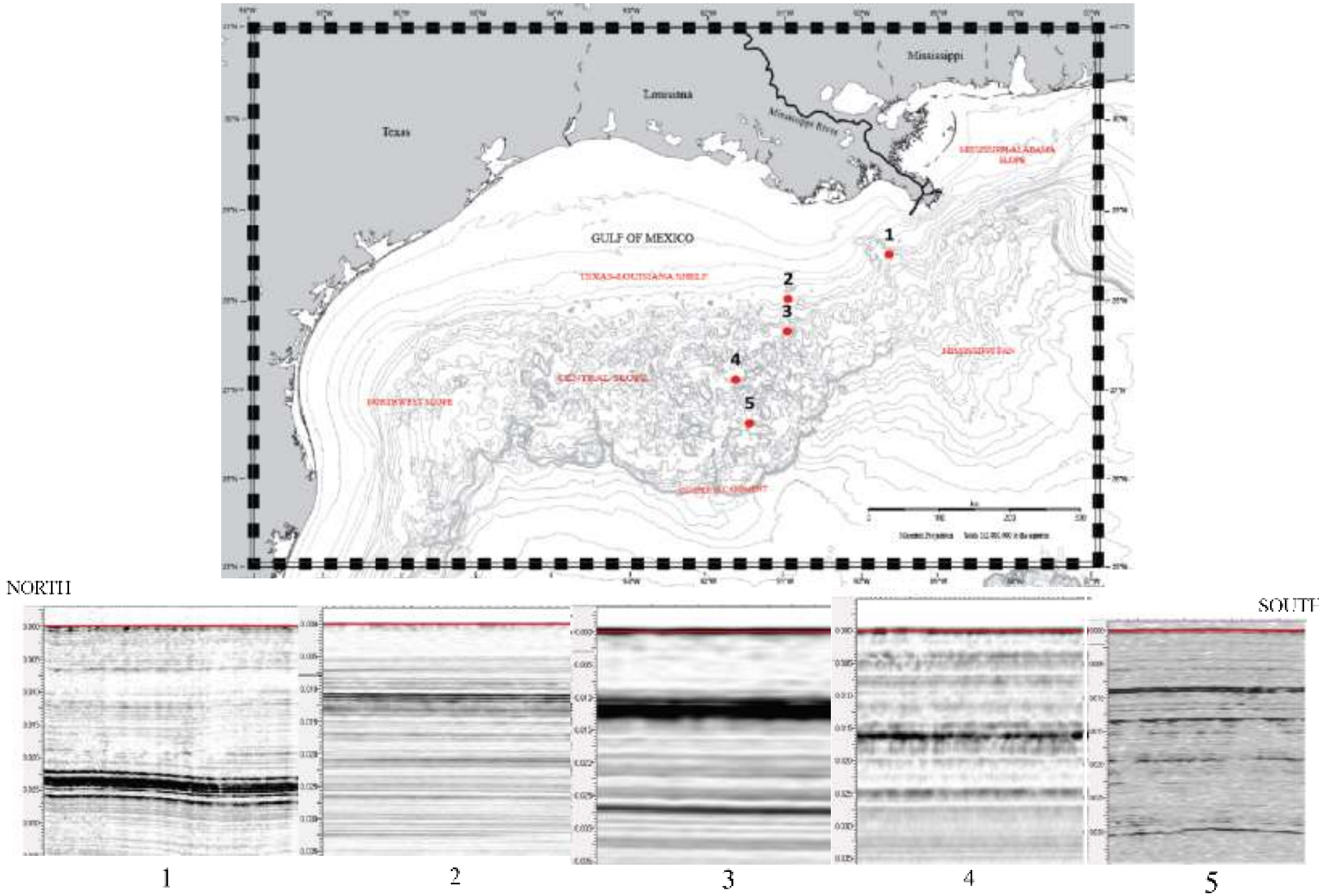


Figure 12. North to South progression of the Triplet in cross-section flattened to seafloor.

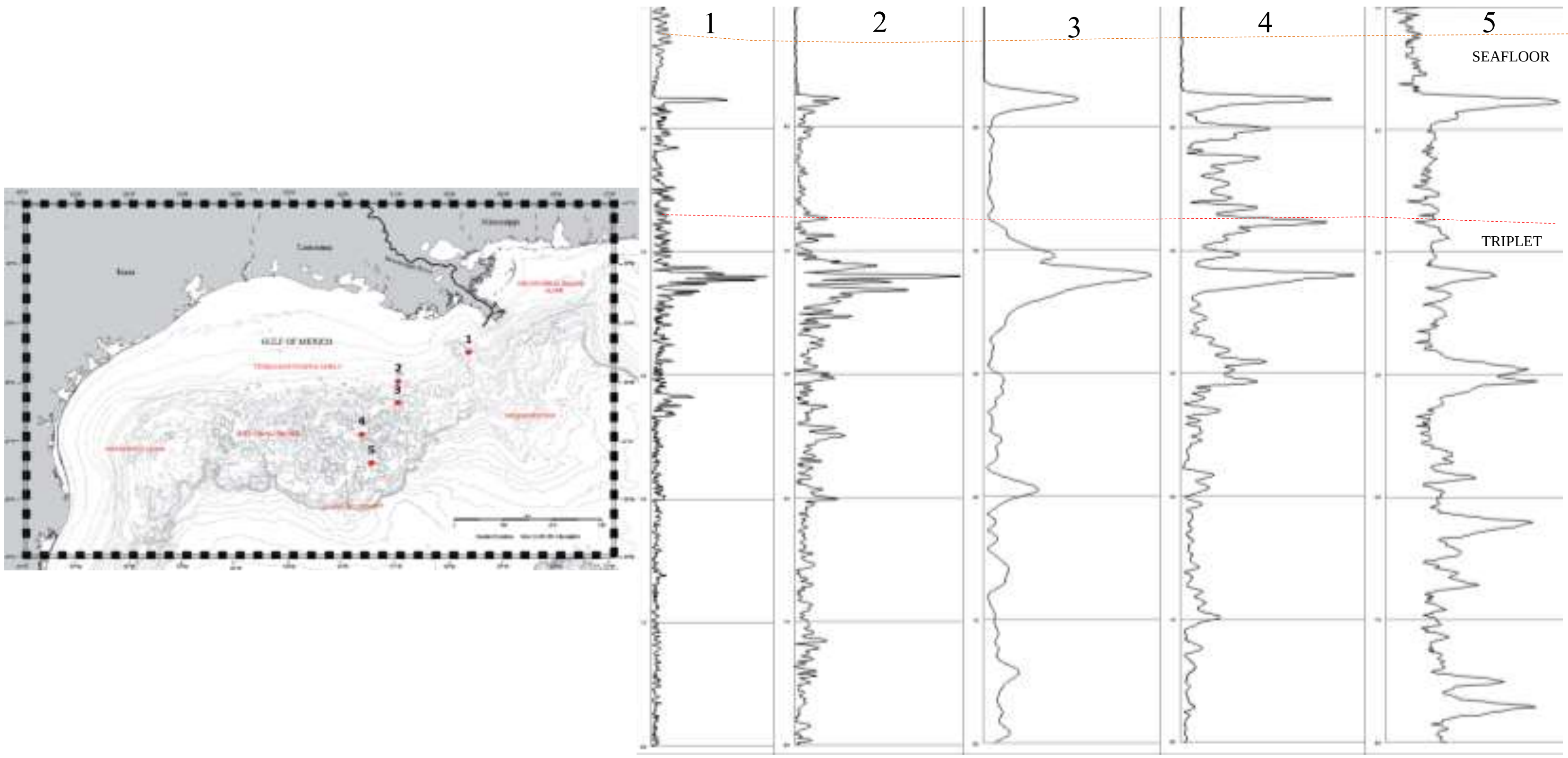


Figure 13. North to South subbottom profile traces. The traces show the remarkable consistency at each location.

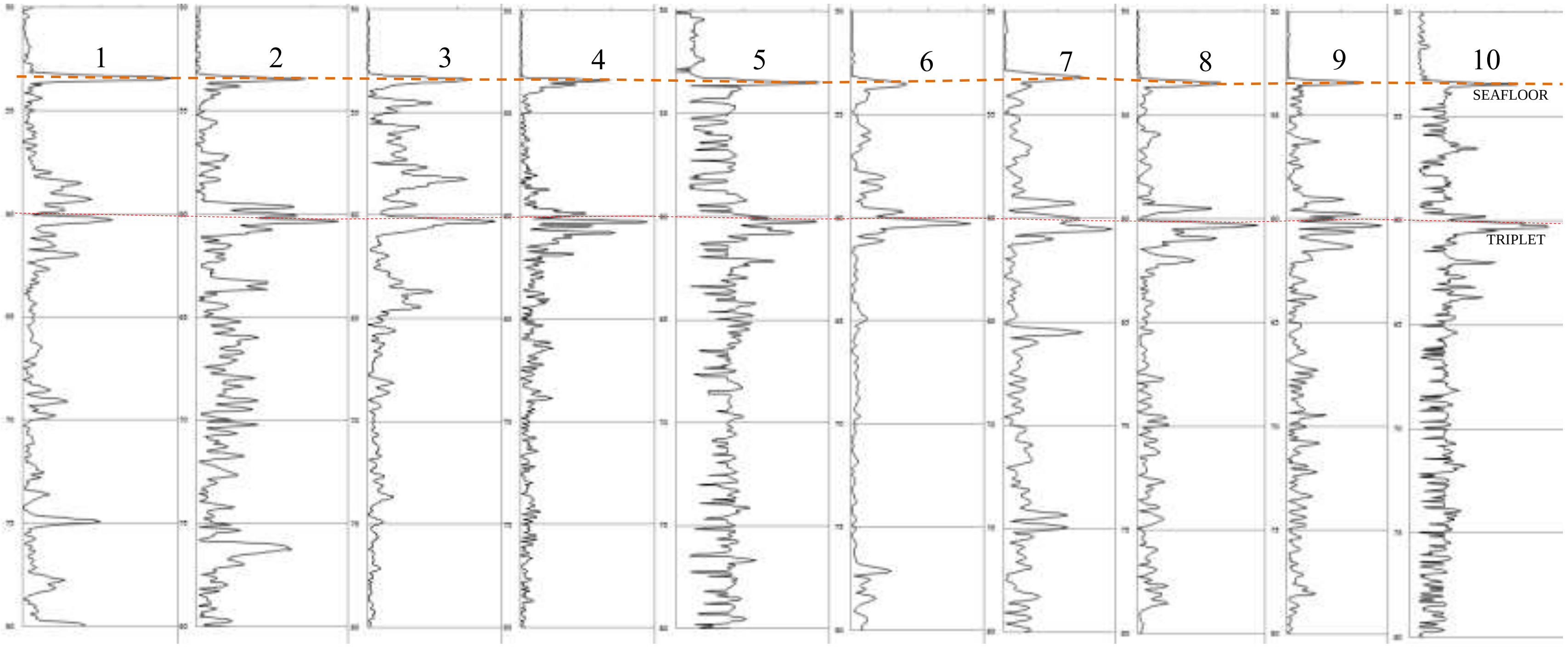
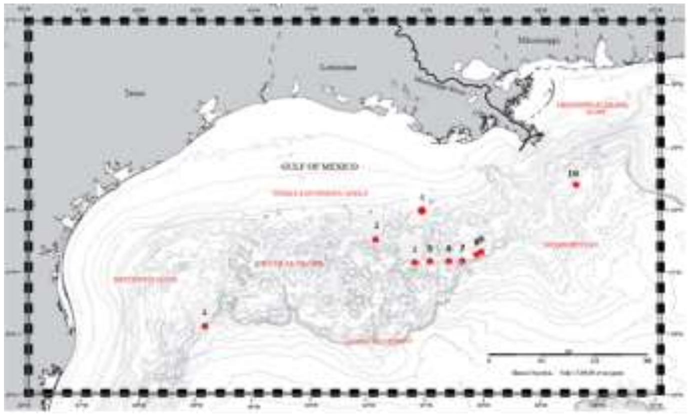


Figure 14. East to West subbottom profile traces. The traces show the positive correlation for each project site.



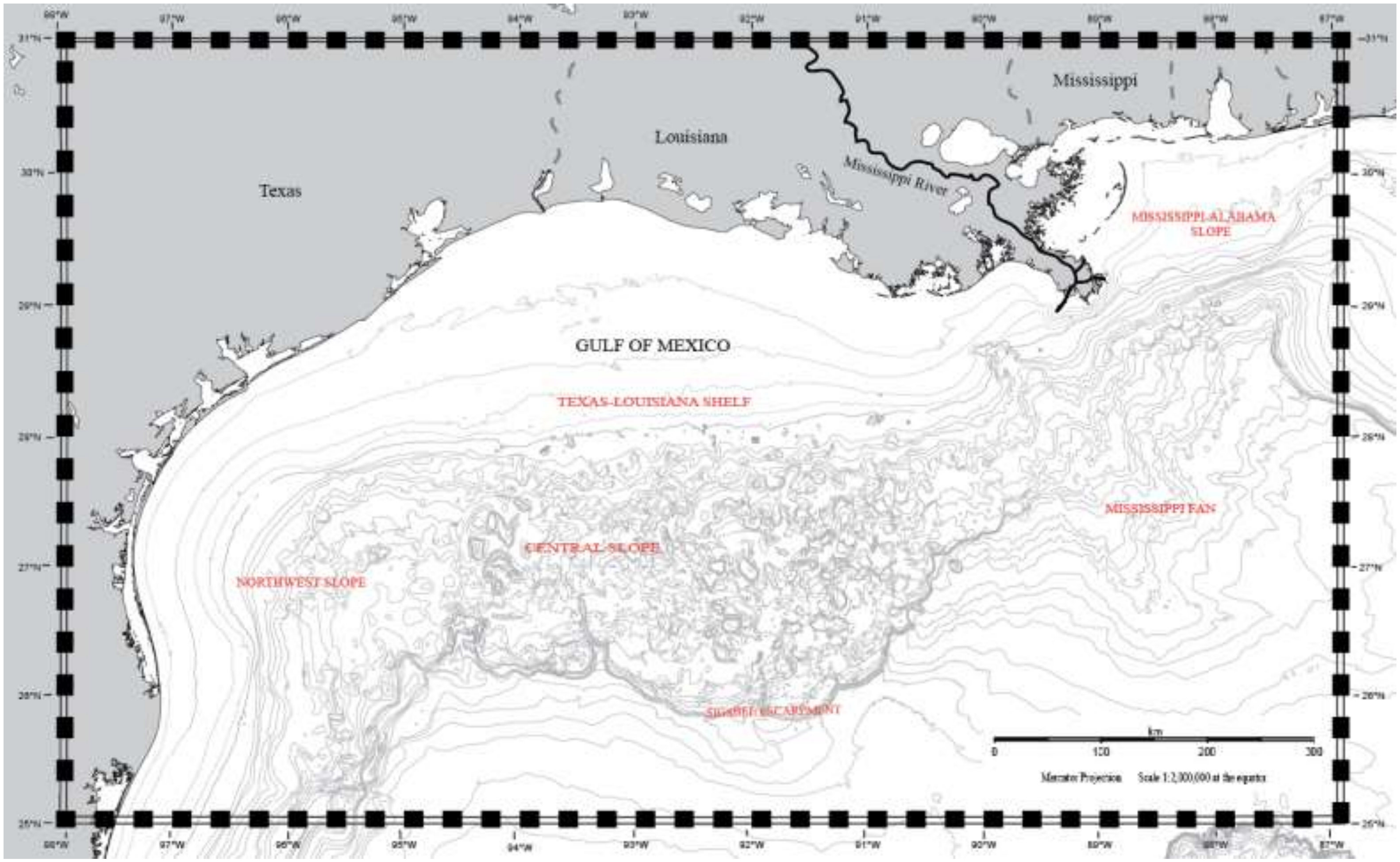


Figure 15a. Map of the Gulf of Mexico corresponding to figures 15b-d.

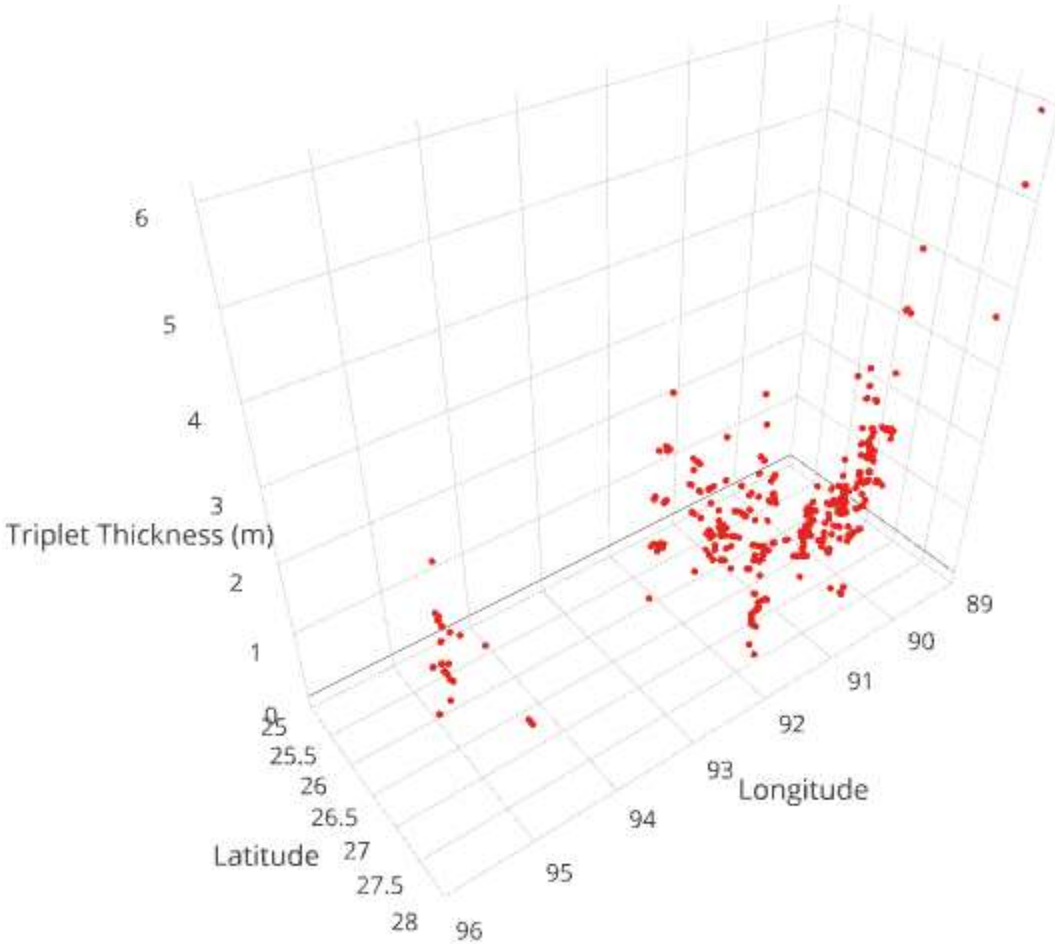


Figure 15b. Scatter Plot: Triplet thickness (m.) versus latitude and longitude.

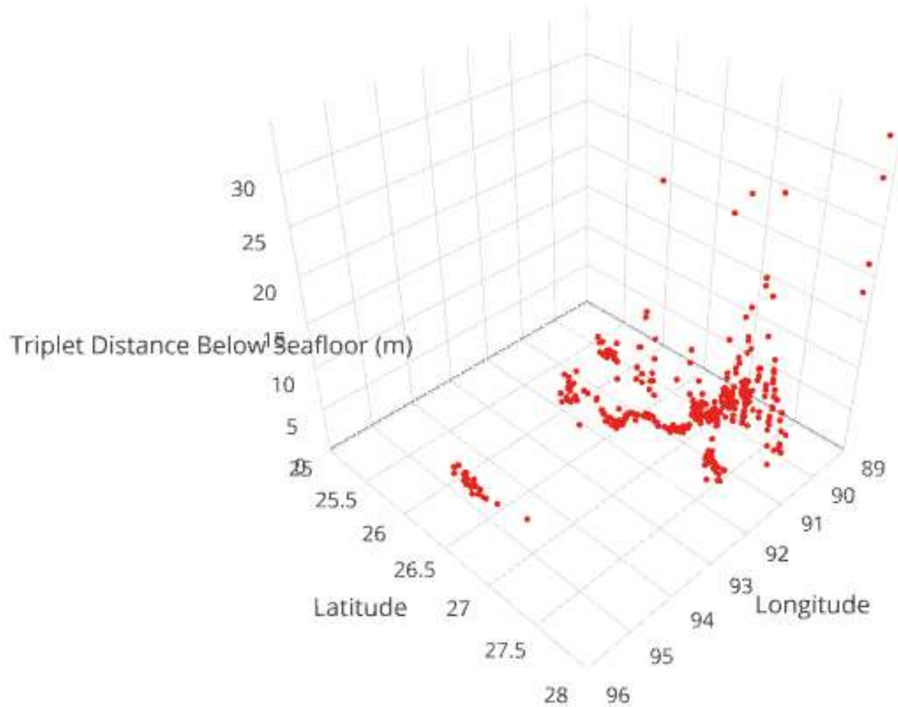


Figure 15c. Scatter Plot: Distance below seafloor (m.) versus latitude and longitude.

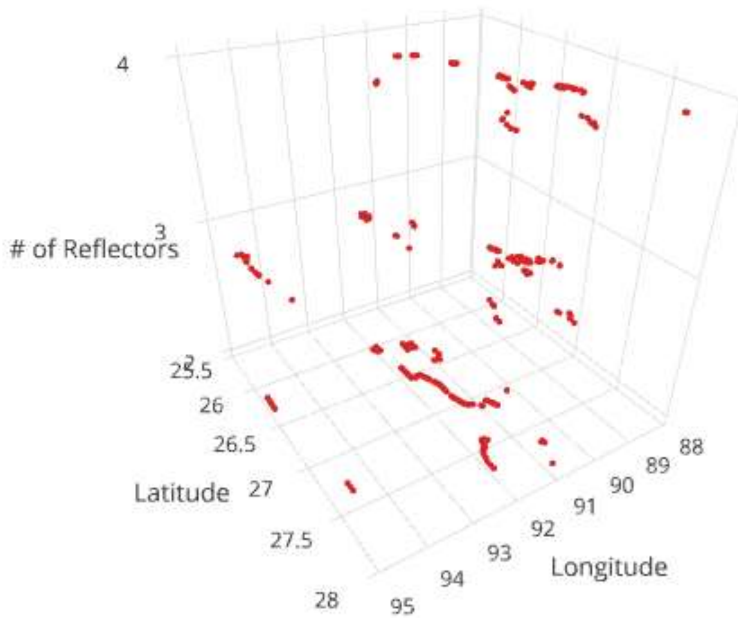


Figure 15d. Scatter Plot: Number of reflectors versus latitude and longitude.

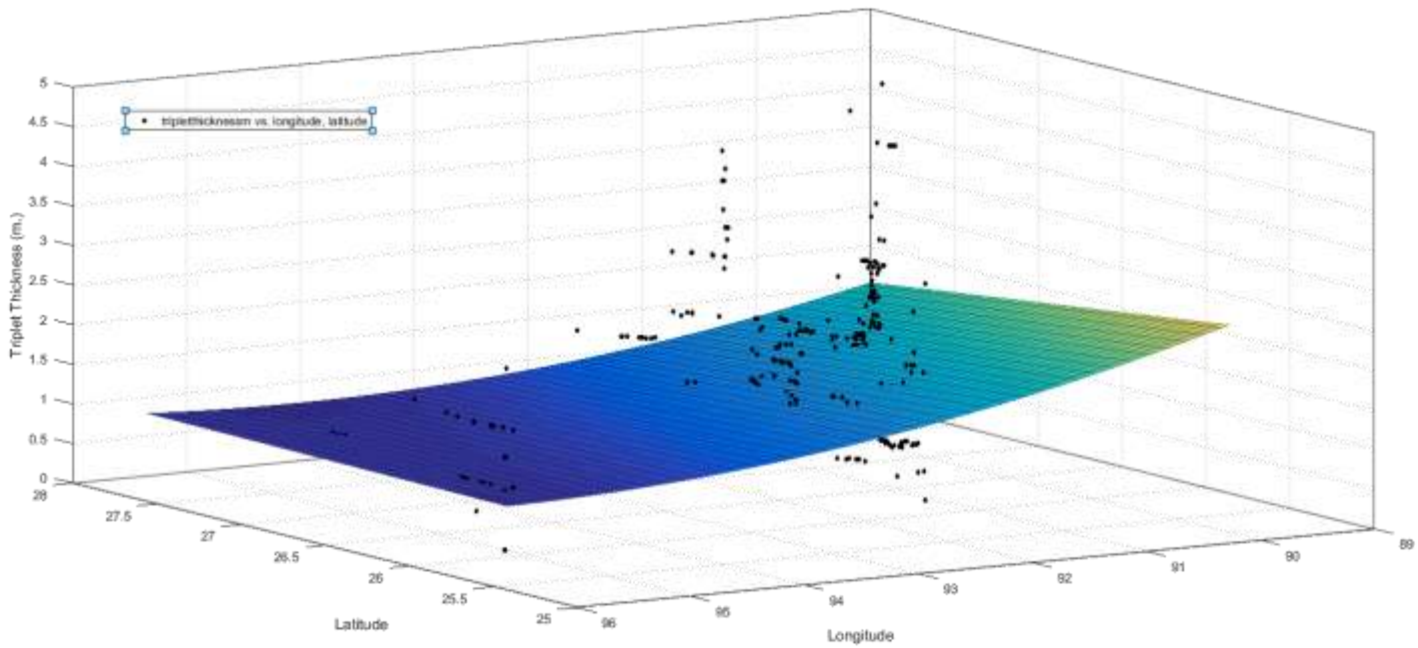


Figure 16. Second order polynomial surface representing data trend. This figure shows the overall trend of the number of reflectors that comprise the Triplet vs. Latitude and Longitude.

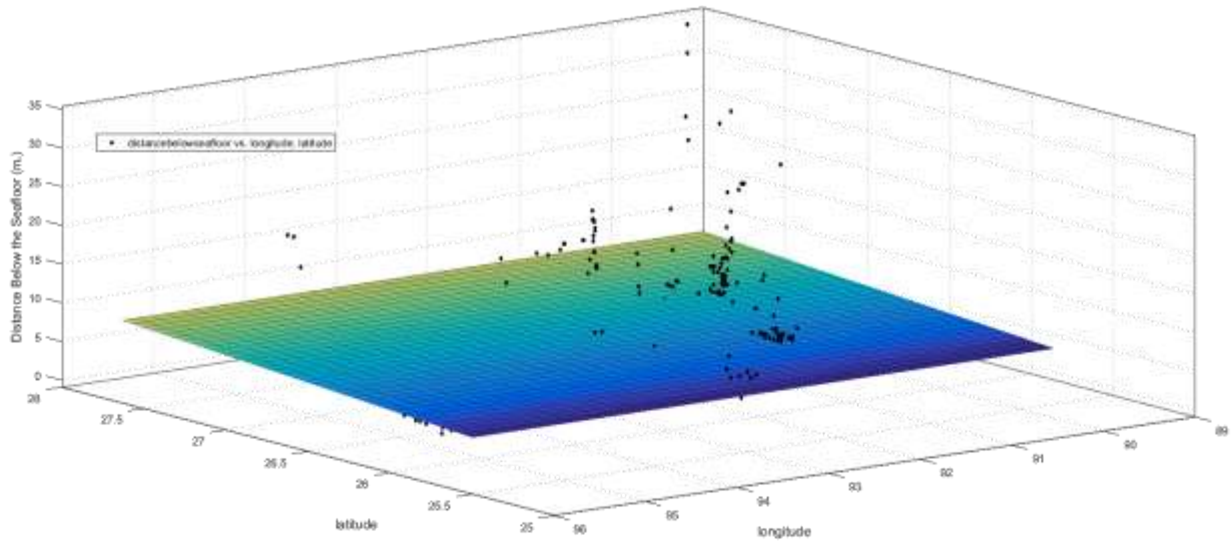


Figure 17. First order polynomial surface fit representing the overall trend of the distance below the seafloor vs. Latitude and Longitude.

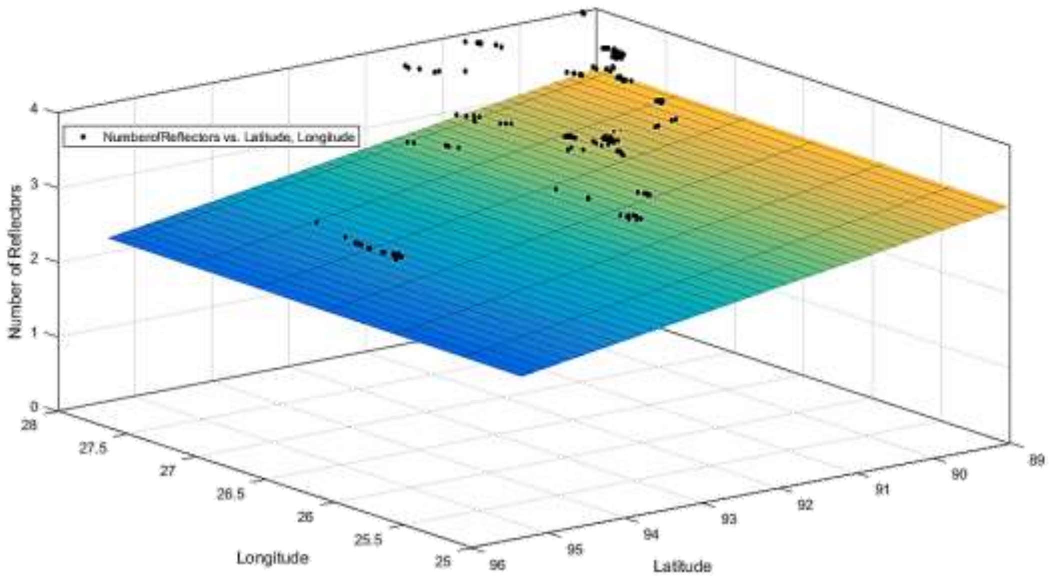


Figure 18. First order polynomial surface fit representing the overall trend of the number of reflectors that comprise the Triplet vs. Latitude and Longitude.

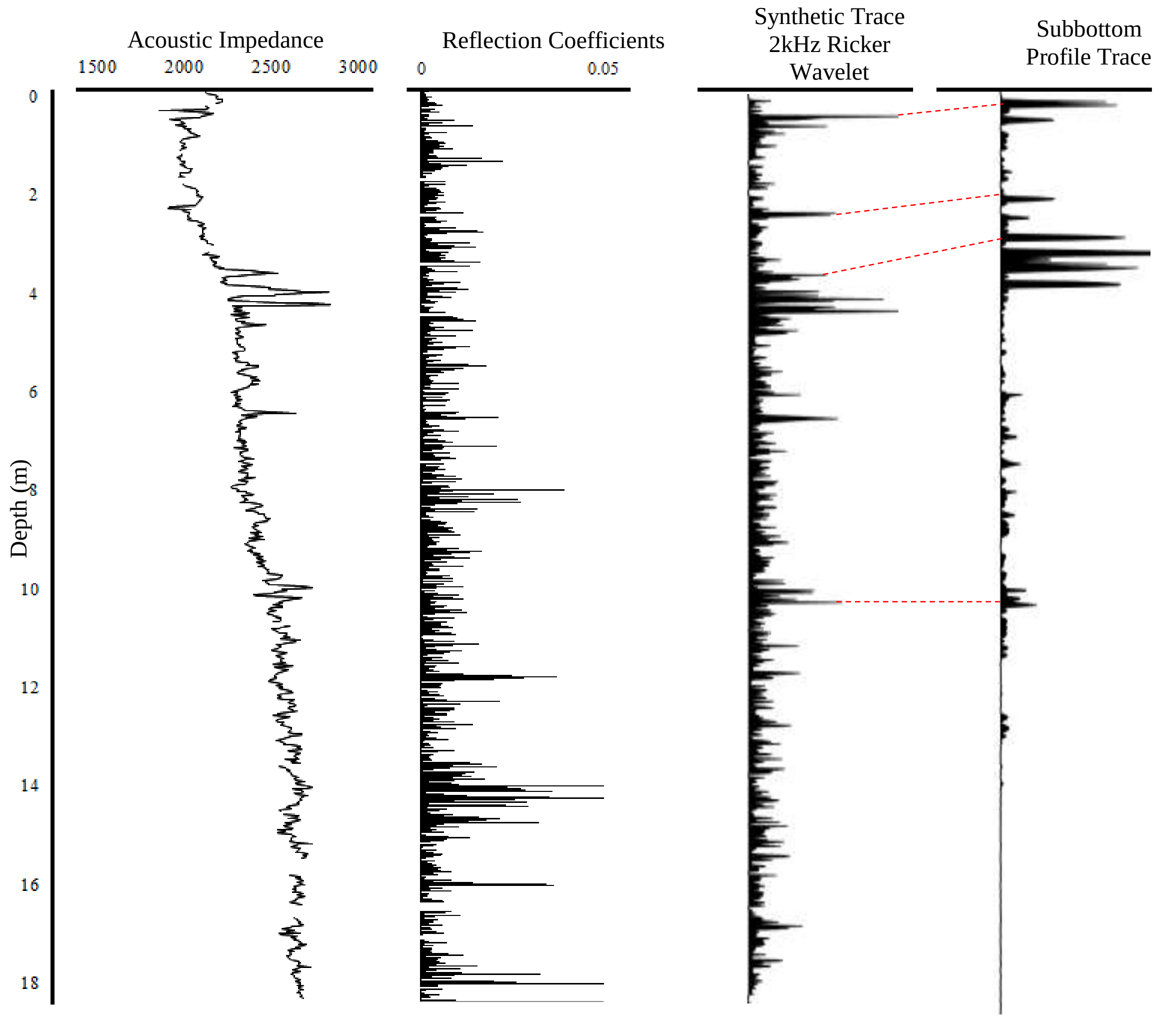


Figure 19. Synthetic seismogram generated using a 2kHz wavelet. Included are the acoustic impedance, reflection coefficients, synthetic seismogram, and corresponding subbottom profile trace. The synthetic seismogram was generated in Matlab. The absolute value of the reflection coefficients was taken to show only positive values similar to the subbottom profile trace. The red dashed lines indicate the correlation between the synthetic trace and the actual subbottom trace.

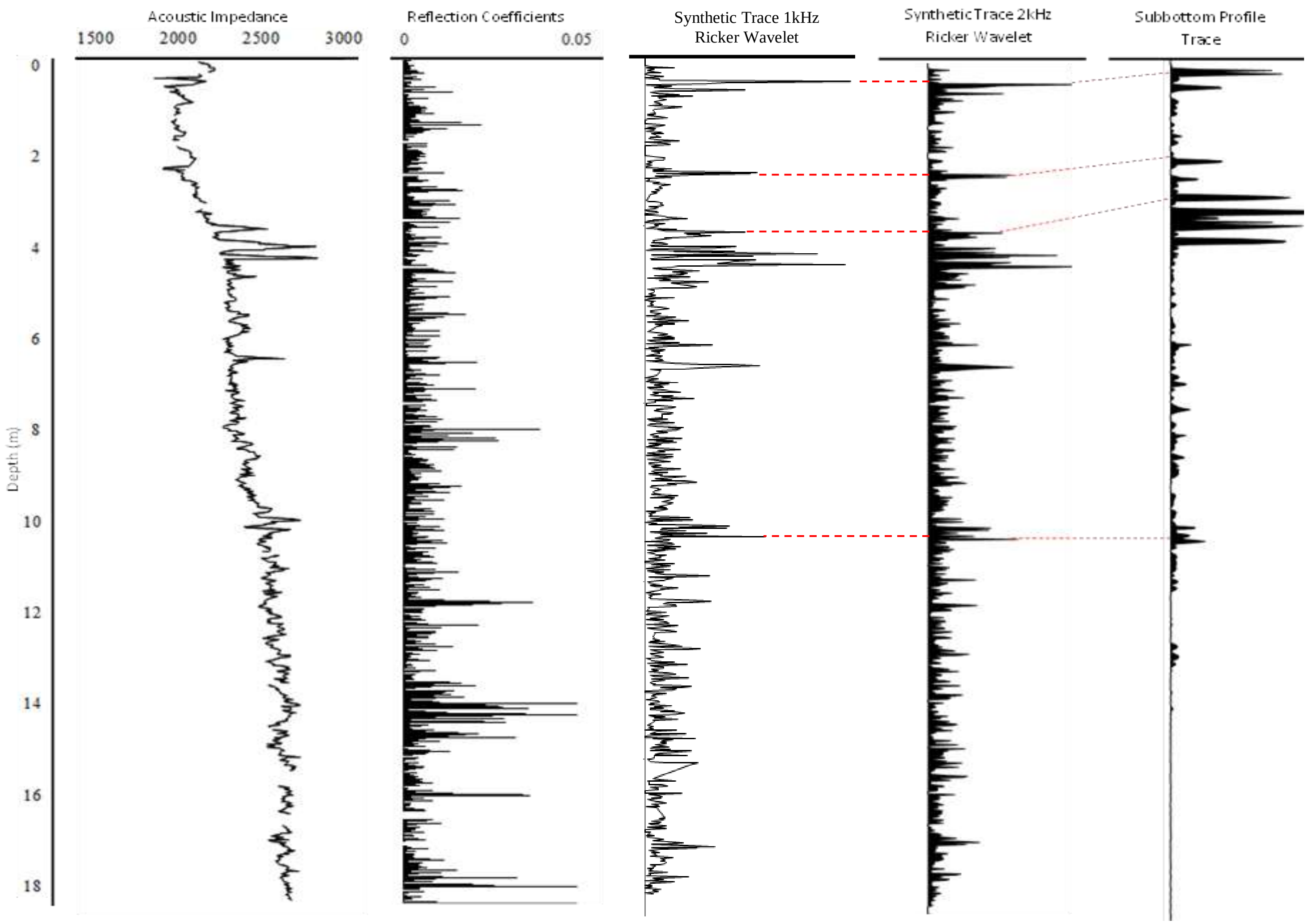


Figure 20. Synthetic seismogram comparison between 1kHz and 2kHz generated ricker wavelet.

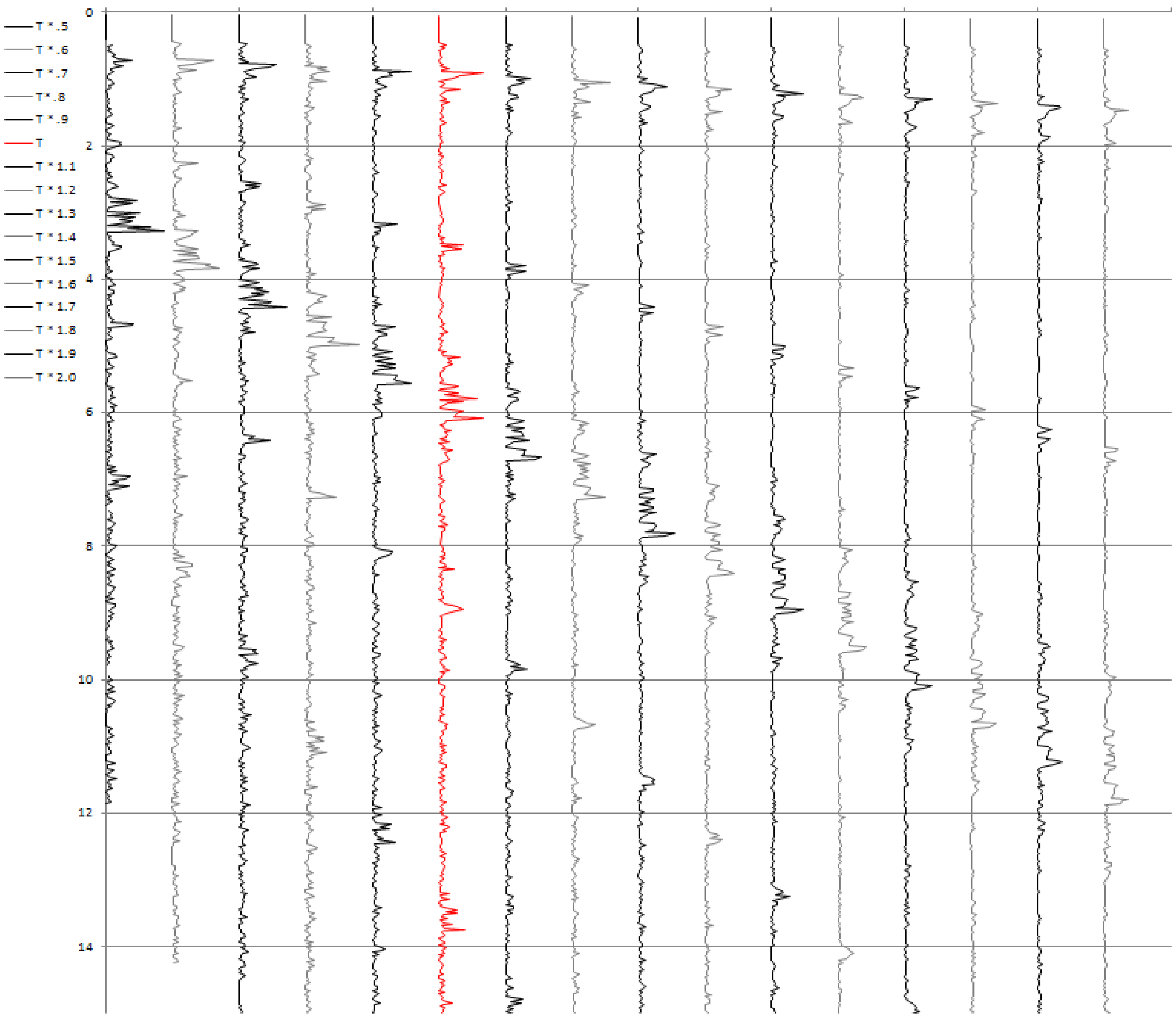


Figure 21. Synthetic seismogram modeling sedimentation rates at an incrementally increasing sedimentation rate CSS-1 (10% increments).